PDF Flavor Determination and the nCTEQ15 PDFs: W ± / Z vector boson production in heavy ion collisions

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Abstract: Recent LHC W/Z vector boson production data in proton-lead collisions are quite sensitive to the heavier flavors (especially the strange PDF), and this complements the information from neutrino-DIS data. As the proton flavor determination is dependent on nuclear corrections (from heavy target DIS, for example), LHC heavy ion measurements can also help improve proton PDFs. We introduce a new implementation of the nCTEQ code (nCTEQ++) based on C++ which has a modular strucure and enables us to easily integrate programs such as HOPPET, APPLgrid, and MCFM. Using ApplGrids generated from MCFM, we use nCTEQ++ to perform a fit including the p-Pb LHC W/Z vector boson data.

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PROCEEDINGS OF SCIENCE

PDF Flavor Determination and the nCTEQ PDFs:

$W^{\pm}/Z$ vector boson production in heavy ion collisions

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Recent LHC $W^{\pm}/Z$ vector boson production data in proton-lead collisions are quite sensitive to the heavier flavors (especially the strange PDF), and this complements the information from neutrino-DIS data. As the proton flavor determination is dependent on nuclear corrections (from heavy target DIS, for example), LHC heavy ion measurements can also help improve proton PDFs. We introduce a new implementation of the nCTEQ code (**nCTEQ++**) based on C++ which has a modular strucure and enables us to easily integrate programs such as HOPPET, APPLgrid, and MCFM. Using ApplGrids generated from MCFM, we use **nCTEQ++** to perform a fit including the *pPb* LHC $W^{\pm}/Z$ vector boson data.

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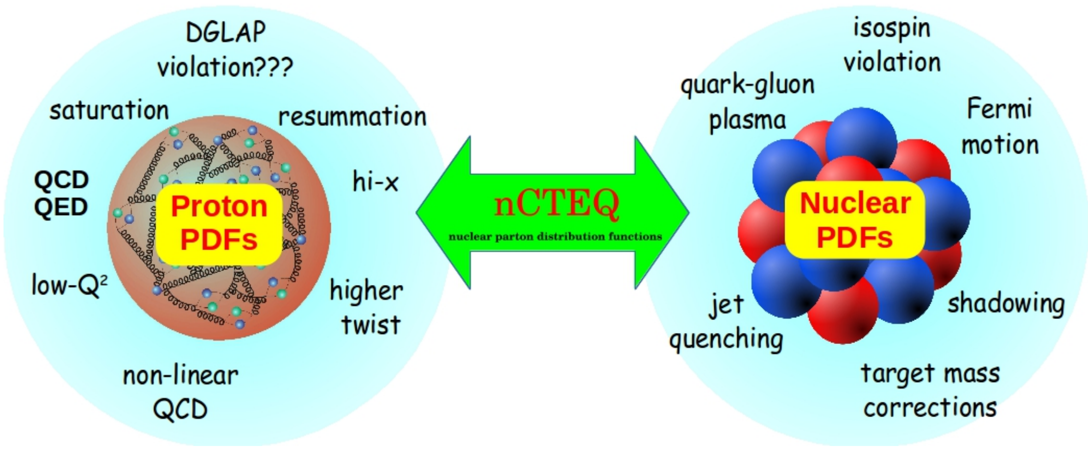

Figure 1: Schematic representation of selected phenomenological issues that can impact the determination of proton and nuclear PDFs.[1]

1. Introduction

The Parton Distribution Functions (PDFs) are the key ingredient that enables us to connect experiment with theory using the QCD improved parton model to describe the distribution of quarks and gluons in the proton. Despite decades of studies, there is yet much to learn about the proton structure.

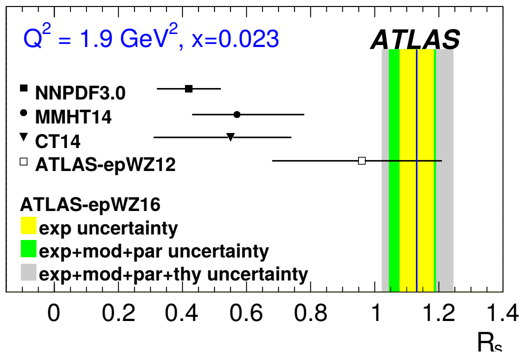

Figure 2: The relative quark ratio $R_s = (s+\bar{s})/(\bar{u}+\bar{d})$ as measured by the ATLAS collaboration from W/Z production in proton-proton collisions [2].

A very interesting result which was discussed at this meeting was the ratio of the strange PDF to the up- and down-sea quark PDFs extracted using $W^{\pm}/Z$ production (a "standard candle" measurement) at the LHC as shown in Figure 2. This case is just one example where improved determinations of the PDFs can significantly impact precision theoretical predictions, and thus enhance our ability to discern "new physics" signatures from uncertain "standard model" processes. The goal of the nCTEQ collaboration is to make maximal use of the available data, both proton and nuclei, to obtain the most precise determination of the PDFs. In this brief report, we summarize some of the recent advancements toward this goal.

2. The nCTEQ Project

The nCTEQ project[1] is built upon the work of the CTEQ proton PDF global fitting effort by extending the fit degrees of freedom into the nuclear dimension. Previous to the nCTEQ effort, nuclear data was "corrected" to isoscalar data and added to the proton PDF fit *without* any uncertainties. In contrast, the nCTEQ framework allows full communication between the nuclear

[1]For details, see `www.ncteq.org` which is hosted at HepForge.org.

data and the proton data, as illustrated schematically in Fig. 1. This enables us to investigate if observed tensions between data sets could potentially be attributed to the nuclear corrections.

The details of the nCTEQ program are presented in Ref. [1]. The analysis includes Deeply Inelastic Scattering (DIS), lepton pair production (Drell-Yan), and pion production from a variety of experiments totaling 740 data (after cuts) and 19 nuclei. The computed PDFs compare favorably to other determinations from the literature [3–5].

3. LHC Heavy Ion W Production and Correlations

In this report, we will focus on $W^{\pm}/Z$ production as this process is sensitive to the heavier flavors. In Fig. 3 we display the correlations between W^{+} and W^{-} cross sections for proton-lead interactions calculated with different input PDFs and assumptions [6]. By comparing the results with and without the $\{s,c,b\}$ flavors, we see the heavier quarks do have a large impact on this observable; hence, this process can provide incisive information about the corresponding PDFs.

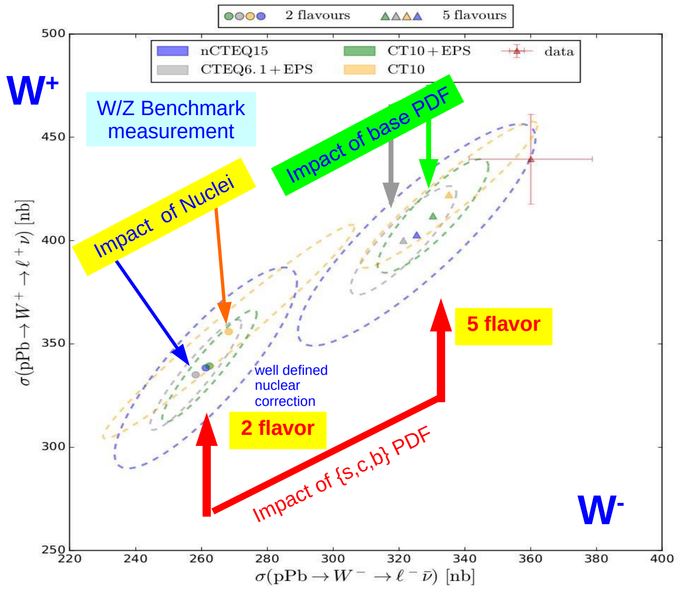

Figure 3: Correlations between W^{+} and W^{-} cross sections calculated with different input PDFs and assumptions for the *pPb* process. The upper-right ellipse is computed with all 5 flavors, and the lower-left ellipse includes only the $\{u,d\}$ partons. We show here results for nCTEQ15, EPS09+CT10, EPS09+CTEQ6.1 and CT10 PDFs with the CMS data.

To see the effect of the nuclear corrections, we can compare the CT10 proton result with the other calculations. We observe that for the case of 2 flavors only, the separation of the proton result (CT10) and the nuclear results are quite distinct. In this case, the effect of the specific nuclear correction (nCTEQ15 or EPS09) or the effect of the underling base PDF (CTEQ6.1 or CT10) is minimal.

In contrast, when we compare this picture to the 5 flavor results, the division between the proton and nuclear result is not as simple as the different nuclear corrections and base PDFs yield a broader range of results. In particular, we note that the strange quark PDFs in the CTEQ6.1 and CT10 base PDFs are quite different, and this will contribute to the spread of results.

Thus, proton-lead production of $W^{\pm}/Z$ is an ideal "laboratory" as this process is sensitive to i) the heavy flavor components, ii) the nuclear corrections, and iii) the underlying "base" PDF.

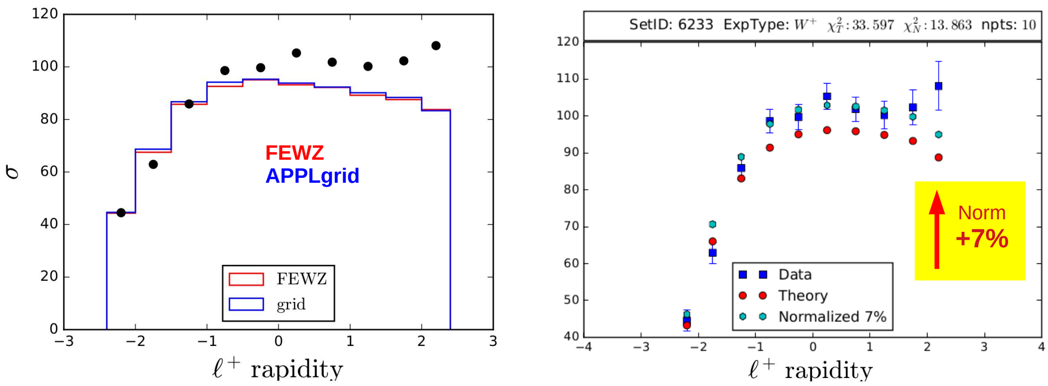

Figure 4: a) Theory predictions for W^+ production in pPb from FEWZ (red), an APPLgrid calculation (blue), and the associated CMS data set (black points). The APPLgrids were generated using replica grids from MCFM in pp mode, and then applied to the pPb calculation. b) A Sample comparison of nCTEQ+LHC fit to the CMS data as well as a (2σ) normalized theory prediction.

4. The **nCTEQ++** Program & Fast Grid Computations

The original nCTEQ project was based on the Fortran 77 proton PDF framework.[7] As the scope of this project has grown, it was necessary to restructure the nCTEQ code to make it more modular. The new **nCTEQ++** program is C++ running on top of legacy Fortran; the evolution is performed by a modified version of HOPPET[8] (extended to accommodate grids of multiple nuclei), and the output of the fit is exported in YAML format and then processed by Python Jupyter notebooks.

If we are to include complex NLO processes into our PDF fit in an efficient manner, it is essential to make use of the grid tools such as APPLgrid,[9] and we have implemented these techniques into our new **nCTEQ++** framework. Specifically, **nCTEQ++** uses pre-computed APPLgrid grids generated by the MCFM Fortran program[10] to perform fast NLO and NNLO $W^{\pm}/Z$ calculations inside the Minuit fitting loop. We demonstrate the advantages of these features below.

In Figure 4-a) we validate our grid implementation for nuclear $W^{\pm}/Z$ production. The FEWZ cross section[11] (red histogram) was computed using a modified version of the standard FEWZ program to accommodate the proton-lead initial state.[6] Although such modifications are technically straightforward, their systematic implementation and cross-checking is time consuming nevertheless. In contrast for the APPLgrid calculation (blue histogram), the MCFM program was used (in proton-proton mode) to generate a collection of grids. If sufficient statistics are used, the combined grids are independent of the initial PDF.

> Thus, we can generate grids in proton-proton mode, but then use them also for proton-nucleus or nucleus-nucleus processes!

The fact that the red and blue histograms match within statistical accuracy validates this approach.

Moreover, now that we have implemented this APPLgrid framework, we have access to all the ∼1000 processes included in MCFM.[2] We now illustrate the utility of this flexible modular framework by performing a (preliminary) fit including the LHC $W^{\pm}/Z$ heavy ion data.

5. PDF fit to LHC $W^{\pm}/Z$ Data

Now that we can compute fast NLO (or NNLO) $W^{\pm}/Z$ cross sections, we can include these directly into our PDF fits. A sample comparison is displayed in Figure 4-b). The data for CMS $W^{+}$are shown as blue squares with error bars, and the theory in the red circles. For comparison, we also present the theory with a 7% normalization shift applied; the quoted luminosity uncertainty is 3.5%.

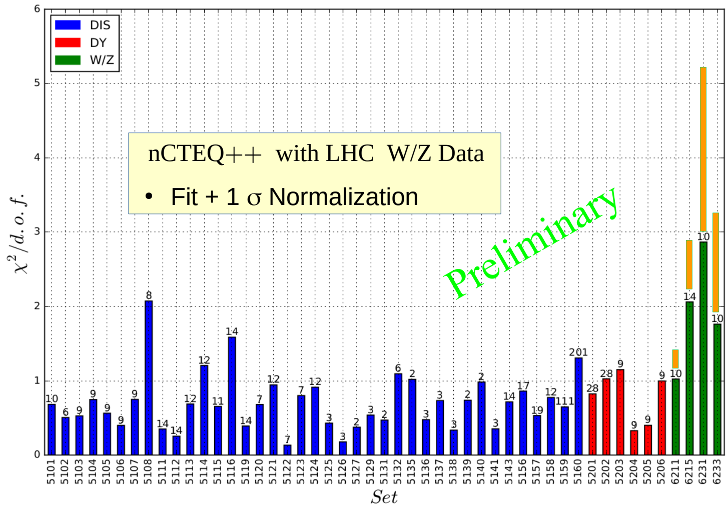

Figure 5: $\chi^2/d.o.f$ for each data set included in nCTEQ+LHC. The individual data sets are identified by the ID number corresponding to those in Ref. [6]. The LHC $W^{\pm}/Z$ data is displayed in green and have ID numbers corresponding to 62XX; in this fit, we have allowed a floating normalization of 1 σ.

In Figure 5 we show the computed χ^2 results for the individual experiments before and after our fit. As we are only opening up a limited number of parameters in this preliminary fit, it is primarily the LHC $W^{\pm}/Z$ data that is affected.[3] The separate processes in the figure are color coded. The DIS data is represented by blue bars and the Drell-Yan data by red bars; χ^2 of these data sets is essentially unchanged. The $W^{\pm}/Z$ is represented by the green bars, and the orange bars show the change in χ^2 before and after the fit. We have allowed a variable normalization of the data (with an appropriate χ^2 penalty); our preliminary results indicated a normalization shift of 1σ (2.7% for ATLAS and 3.5% for CMS) yield near optimal values.[4]

We see that by including the $W^{\pm}/Z$ data into the fit we are able to obtain a much improved description of this data set. A full fit (with a full set of free parameters) is underway, but this preliminary fit with a limited set of free parameters is sufficient to demonstrate the merits the new **nCTEQ++** code with the grid-based computations.

[2] For example, a recent study [12] uses heavy flavor meson data to constrain the gluon distribution; this data can also can be included using APPLgrid techniques.

[3] Specifically, we fit 12 parameters: 3 for $s+\bar{s}$, and the remaining 9 for $\{g, u_V, d_V, \bar{u}+\bar{d}\}$. This is in contrast to nCTEQ15 which fits 16 parameters for $\{g, u_V, d_V, \bar{u}+\bar{d}\}$ and keeps the strange PDF fixed.

[4] In Fig. 4-b) we display a normalization shift of 2σ for illustration purposes; however, when the normalization penalty is included, the 1σ shift yields a lower total χ^2.

6. Conclusion

The goal of the nCTEQ project is to obtain the most precise PDFs using the full collection of both proton and nuclear data. In this brief report we have observed that the LHC heavy ion data can help determine nuclear corrections for large A values in a kinematic $\{x, Q^2\}$ range very different from those provided by fixed-target measurements.

The $W^{\pm}/Z$ pPb data are particularly sensitive to the heavier quark flavors (especially the strange PDF), so this provides important information on the flavor decomposition. The new **nCTEQ++** framework, which integrates the NLO grid calculations, allows us to easily include these processes into the PDF fit.

Improved information on the nuclear corrections from the LHC lead data can also help reduce proton PDF uncertainties as (at present) fixed-target nuclear data is essential for distinguishing the individual flavors [13]. The next step is to extend the above preliminary fit with a complete set of free parameters and additional data sets to help separately disentangle issues of flavor differentiation and nuclear corrections.

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